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REVIEW

Passive ultrasonic irrigation of the root canal: a review of the literature

L. W. M. van der Sluis[1], M. Versluis[2], M. K. Wu[1] & P. R. Wesselink[1]

[1]Department of Cariology Endodontology Pedodontology, Academic Centre for Dentistry Amsterdam (ACTA), Amsterdam, The Netherlands; and [2]Physics of Fluids group, Science and Technology, University of Twente (UT), Enschede, The Netherlands

Abstract

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Ultrasonic irrigation of the root canal can be performed with or without simultaneous ultrasonic instrumentation. When canal shaping is not undertaken the term passive ultrasonic irrigation (PUI) can be used to describe the technique. In this paper the relevant literature on PUI is reviewed from a MEDLINE database search.Passive ultrasonic irrigation can be performed with a small file or smooth wire (size 10–20) oscillating freely in the root canal to induce powerful acoustic microstreaming. PUI can be an important supplement for cleaning the root canal system and, compared with traditional syringe irrigation, it removes more organic tissue, planktonic bacteria and dentine debris from the root canal. PUI is more efficient in cleaning canals than ultrasonic irrigation with simultaneous ultrasonic instrumentation. PUI can be effective in curved canals and a smooth wire can be as effective as a cutting K-file. The taper and the diameter of the root canal were found to be important parameters in determining the efficacies of dentine debris removal. Irrigation with sodium hypochlorite is more effective than with water and ultrasonic irrigation is more effective than sonic irrigation in the removal of dentine debris from the root canal. The role of cavitation during PUI remains inconclusive. No detailed information is available on the influence of the irrigation time, the volume of the irrigant, the penetration depth of the instrument and the shape and material properties of the instrument. The influence of irrigation frequency and intensity on the streaming pattern as well as the complicated interaction of acoustic streaming with the adherent biofilm needs to be clarified to reveal the underlying physical mechanisms of PUI.

Keywords: biofilm, cleaning, dentine debris, irrigation, review, root canal, ultrasound.

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Introduction

With the endodontic procedures at our disposal it is impossible to shape and clean the root canal completely. This is mainly due to the complex anatomy of the root canal system (Ricucci & Bergenholtz 2003, Peters 2004, Naïr *et al.* 2005). Irregularities of the root canal wall in particular are a major concern, including oval extensions, isthmuses and apical deltas (Wu & Wesselink 2001, Ricucci & Bergenholtz 2003, Peters 2004, Naïr *et al.* 2005). In fact, within oval canals only 40% of the apical root canal wall area can be contacted by instruments when a rotating technique is used (Wu *et al.* 2003). Therefore, irrigation is an essential part of a root canal treatment as it allows for cleaning beyond the root canal instruments.

The goal of irrigation is to remove pulp tissue and/or microorganisms (planktonic or biofilm) from

Correspondence: L. W. M. van der Sluis, Department of Cariology Endodontology Pedodontology, ACTA, Louwesweg 1, 1066 EA Amsterdam, The Netherlands (Tel.: +31 20 5188651; fax: +31 20 6692881; e-mail: l.vd.sluis@acta.nl).

the root canal system (Haapasalo *et al.* 2005). Irrigation should also remove smear layer and dentine debris that occur following instrumentation of the root canal (Baugh & Wallace 2005). The efficacy of irrigation depends on the working mechanisms of the irrigant and the ability to bring the irrigant in contact with those elements, materials and structures within the canal system, which have to be removed (Rosenfeld *et al.* 1978, Chow 1983). Sodium hypochlorite (NaOCl) is widely used as an endodontic disinfectant that is effective because it can dissolve organic tissue, can kill microorganisms, act as a lubricant and is nontoxic (Haapasalo *et al.* 2005). However, chlorine, which is responsible for the dissolving and antibacterial capacity of NaOCl, is unstable and is consumed rapidly during the first phase of tissue dissolution, probably within 2 min (Moorer & Wesselink 1982); therefore continuous replenishment is essential.

Ultrasonic devices were first introduced in Endodontics by Richman (1957). Ultrasonically activated files have the potential to prepare and debride root canals mechanically. The files are driven to oscillate at ultrasonic frequencies of 25–30 kHz that are beyond the limit of human hearing. The files operate in a transverse vibration, setting up a characteristic pattern of nodes and anti-nodes along their length (Walmsley 1987, Walmsley & Williams 1989). Unfortunately, it proved to be difficult to control the cutting of dentine during ultrasonic preparation, with the result that it is impossible to control the shape of the prepared root canal and apical perforations and irregular shapes were produced (Stock 1991, Lumley *et al.* 1992).

On the other hand it has been shown that ultrasonically driven files are effective for the 'irrigation' of root canals. Two types of ultrasonic irrigation have been described in the literature: one where irrigation is combined with simultaneous ultrasonic instrumentation (UI) and another without simultaneous instrumentation, so called passive ultrasonic irrigation (PUI). During UI the file is intentionally brought into contact with the root canal wall. UI has been shown to be less effective in removing simulated pulp tissue from the root canal system or smear layer from the root canal wall than PUI (Weller *et al.* 1980, Ahmad *et al.* 1987a). This can be explained by a reduction of acoustic streaming and cavitation (Ahmad *et al.* 1987a). As the root canal anatomy is complex (Peters 2004) an instrument will never contact the entire root canal wall (Wu *et al.* 2003). Thus, UI could result in uncontrolled cutting of the root canal wall without effective cleaning.

Passive ultrasonic irrigation was first described by Weller *et al.* (1980). The term 'passive' does not adequately describe the process, as it is in fact active; however, when it was first introduced the term 'passive' related to the 'noncutting' action of the ultrasonically activated file. PUI relies on the transmission of acoustic energy from an oscillating file or smooth wire to an irrigant in the root canal. The energy is transmitted by means of ultrasonic waves and can induce acoustic streaming and cavitation of the irrigant (Ahmad *et al.* 1987a,b, Ahmad *et al.* 1988, Lumley *et al.* 1991, Ahmad *et al.* 1992, Roy *et al.* 1994). After the root canal has been shaped to the master apical file (irrespective of the preparation technique used), a small file or smooth wire (for example size 15) is introduced in the centre of the root canal, as far as the apical region. The root canal is then filled with an irrigant solution and the ultrasonically oscillating file activates the irrigant. As the root canal has already been shaped, the file or wire can move freely and the irrigant can penetrate more easily into the apical part of the root canal system (Krell *et al.* 1988) and the cleaning effect will be more powerful (Ahmad *et al.* 1987a,b,1988,1992, Lumley *et al.* 1991, Roy *et al.* 1994). Using this noncutting methodology, the potential to create aberrant shapes within the root canal will be reduced to a minimum. A file larger than size 15 or 20 will only oscillate freely in a wide root canal. A size 25 file may in fact produce less acoustic streaming than a size 15 and 20 file (Ahmad *et al.* 1987b). Consequently, using a file larger than size 20 may be considered fundamentally different from the basic principle of PUI. The cleaning efficacy of PUI implies the effective removal of dentine debris, microorganisms (planktonic or in biofilm) and organic tissue from the root canal. Because of the active streaming of the irrigant its potential to contact a greater surface area of the canal wall will be enhanced.

The purpose of this review is to evaluate the literature on PUI, to provide a description of the mechanism and its effects and to evaluate if PUI is more effective in cleaning the root canal than syringe irrigation.

Materials and methods

The literature search used the MEDLINE database which goes back to 1965. Reference lists of potentially relevant articles and review articles were also screened for the search strategy. The following combinations of keywords were used for the search strategy:

- 'ultrasound irrigation root canal'
- OR 'ultrasonic irrigation root canal'
- OR 'passive ultrasonic irrigation'
- OR 'ultrasound NaOCl'
- OR 'ultrasonic cavitation root canal'
- OR 'ultrasonic acoustic streaming root canal'
- OR 'ultrasonic bacteria root canal'
- OR 'ultrasonic biofilm root canal'.

Care was taken to include only studies that addressed 'passive' ultrasonic irrigation; studies using UI were excluded. It appeared that there is little consensus about the terminology of ultrasonic irrigation in the literature. For example, PUI occasionally was mentioned, whilst in fact UI was meant. Such discrepancies potentially had a considerable influence on the interpretation of the results of PUI. The papers were screened independently by two reviewers (M-K. W. and L.S.). The quality of the papers was assessed including an evaluation of the study design and statistical tests. Some papers were categorized as observational studies. These studies describe in detail acoustic streaming patterns, cavitation or displacement amplitudes of the file or wire (Ahmad *et al.* 1987a,b, Cameron 1987a,b, Lumley *et al.* 1988, Cameron 1988, Ahmad 1989, Walmsley & Williams 1989, Ahmad 1990, Lumley *et al.* 1991, Ahmad *et al.* 1992, 1993, Lumley & Walmsley 1992, Roy *et al.* 1994, Cameron 1995, Lea *et al.* 2004). Moreover, three review articles on ultrasonic irrigation cleaning were included: Walmsley (1987), Walmsley *et al.* (1991) and Stock (1991).

The search resulted in a total of 74 articles of which 20 were excluded because they did not correspond with the inclusion criteria, one because of insufficient methodology (Teplitsty *et al.* 1987). The articles where the term 'UI' was used instead of 'PU' are listed in Table 1.

Table 1 Articles which were not included because they dealt with ultrasonic instrumentation and not passive ultrasonic irrigation

Cunningham *et al.* (1982), Barnett *et al.* (1985), Chenail & Teplitsky (1985), Langeland *et al.* (1985), Griffiths & Stock (1986), Krell & Johnson (1988), Biffi & Rodrigues (1989), Haidet *et al.* (1989), Rodrigues & Biffi (1989), Walker & del Rio (1989), Archer *et al.* (1992), Baumgartner & Cuenin (1992), Briseno *et al.* (1992), Lumley *et al.* (1992, 1993), Panighi & Jacquot (1995), Guerisoli *et al.* (2002), Siqueira *et al.* (2002), Walters *et al.* (2002)

Different frequencies, intensities and displacement amplitudes of the files were used in the various studies. Whether these parameters influenced the results reported is not known. Other variables that are encountered in laboratory research, e.g. the difference in preoperative status of the teeth, storage media and storage time may also have an influence on the outcome. However, their effect is unknown.

Results

The results of the review are divided into two parts. The first part describes the mechanism of PUI and the second part the effects of PUI.

Mechanism of passive ultrasonic irrigation

Frequency and intensity

An ultrasonic device converts electrical energy into ultrasonic waves of a certain frequency by magnetostriction or by piezoelectricity. On one hand, magnetostriction is generated by the deformation of a ferromagnetic material subjected to a magnetic field; on the other hand piezoelectricity is the generation of stress in dielectric crystals subjected to an applied voltage. Piezoelectricity was used in the studies of Goodman *et al.* (1985), Ahmad *et al.* (1992, 1993), Cheung & Stock (1993), Lee *et al.* (2004a,b) and van der Sluis *et al.* (2005a,b, 2006). Only one pilot study was undertaken to compare devices using magnetostriction or piezoelectricity at different intensities, however, no conclusive evidence was provided (Cameron 1995).

The properties of the ultrasonic material determine the frequency of the oscillating instrument, which in dental practice, is fixed at 30 kHz. The intensity or energy flux, expressed in units of Watt cm^{-2}, of the oscillating instrument can be adjusted by the power setting. Frequency and intensity do play a role in the transmission of energy from the ultrasonically oscillating file to the irrigant but a full understanding of the mechanism is still lacking. A higher frequency should in principle result in a higher streaming velocity of the irrigant, as will be addressed later. This in turn results in a more powerful acoustic streaming. Increasing the intensity does not result in a linear increase of the displacement amplitude of the oscillating file (Ahmad *et al.* 1987a, Walmsley & Williams 1989, Lea *et al.* 2004). However, this observation is taken from studies that investigated the oscillation of the file in free air. Therefore, a direct relationship with acoustic microstreaming could not be established.

Acoustic streaming

Acoustic streaming is the rapid movement of fluid in a circular or vortex-like motion around a vibrating file (Walmsley 1987). The acoustic streaming that occurs in the root canal during ultrasonic irrigation has been described as acoustic microstreaming. This is defined as the streaming which occurs near small obstacles placed within a sound field, near small sound sources, vibrating membranes or wires, which arise from the frictional forces between a boundary and medium carrying vibrations of circular frequency (Leighton 1994).

Several papers have confirmed that acoustic microstreaming occurs during PUI (Ahmad *et al.* 1987a,b, Walmsley 1987, Walmsley & Williams 1989, Lumley *et al.* 1991, Walmsley *et al.* 1991, Ahmad *et al.* 1992, 1993, Lumley *et al.* 1993, Roy *et al.* 1994) (Fig. 1). The streaming pattern corresponds to the characteristic pattern of nodes and antinodes along the length of the oscillating file.

The displacement amplitude is at its maximum at the tip of the file, probably causing a directional flow to the coronal part of the root canal (Ahmad *et al.* 1987a). When the file touches the root canal wall at an antinode a greater reduction in displacement amplitude will occur compared with when it touches at a node (Walmsley & Williams 1989, Lumley *et al.* 1993). When the file is unable to vibrate freely in the root canal, acoustic microstreaming will become less intense, however, it will not stop completely (Ahmad *et al.* 1988, 1992, Lumley *et al.* 1991, 1993, Roy *et al.* 1994). The resultant acoustic microstreaming depends inversely on the surface area of the file touching the root canal wall.

In curved canals, pre-shaping the file will result in more powerful acoustic microstreaming (Ahmad *et al.* 1992, Lumley *et al.* 1992, Lumley & Walmsey 1992). A pre-shaped file shows the same pattern of nodes and antinodes as a straight file both in air and in the confined geometry of a root canal (Lumley & Walmsley 1992).

The intensity of the acoustic microstreaming is directly related to the streaming velocity. The equation that in first approximation describes the streaming velocity is

$$v = \frac{\omega \varepsilon_0^2}{a}, \qquad (1)$$

where v is the liquid streaming velocity, ω is 2π times the driving frequency, ε_0 is the displacement amplitude and a the radius of the wire. Following equation 1 it can be concluded that the thinner the file, the higher the frequency and the greater the displacement amplitude of the file, the higher the streaming velocity and the more powerful the acoustic microstreaming will be. Whether this equation will also hold for the complicated nonlinear streaming pattern during PUI remains to be shown.

The shear flow caused by acoustic microstreaming produces shear stresses along the root canal wall, which can remove debris and bacteria from the wall. The shear stress is expressed in the following equation (Ahmad *et al.* 1988):

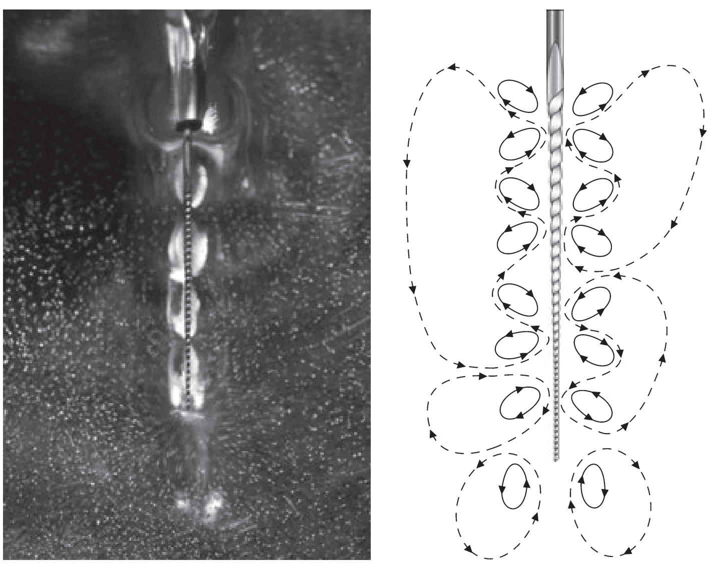

Figure 1 Acoustic streaming around a file in free water (left) and a schematic drawing (right).

$$\tau = \eta\dot{\gamma} = \eta\frac{V}{\delta} = \frac{\eta\omega\varepsilon_0^2}{a\delta}, \quad (2)$$

where η the kinematic viscosity of the liquid, V the streaming velocity (from equation 1) and δ the boundary layer thickness. This equation is an approximation and it remains to be shown whether it is applicable to the typical, more complex, flow conditions of the root canal.

Cavitation and cavitational microstreaming

Cavitation in the fluid mechanical context can be described as the impulsive formation of cavities in a liquid through tensile forces induced by high-speed flows or flow gradients. These bubbles expand and then rapidly collapse producing a focus of energy leading to intense sound and damage, e.g. pitting of ship propellers and pumps. Acoustic cavitation can be defined as the creation of new bubbles or the expansion, contraction and/or distortion of pre-existing bubbles (so-called nuclei) in a liquid, the process being coupled to acoustic energy (Leighton 1994). Cavitation is beneficially used in industrial ultrasound cleaning (Moholkar *et al.* 2004), megasonic chip cleaning (Kern 1990), lithotripsy (Church 1989) and even by small shrimp to stun prey (Versluis *et al.* 2001). In this review the term cavitation refers to acoustic cavitation.

According to Roy *et al.* (1994), two types of cavitation could occur during PUI of root canals: stable cavitation and transient cavitation. Stable cavitation could be defined as linear pulsation of gas-filled bodies in a low amplitude ultrasound field. Transient cavitation occurs when vapour bubbles undergo highly energetic pulsations (Fig. 2). When the acoustic pressures are high enough, the bubbles can be inertially driven to a violent collapse, radiating shock waves and generating high internal gas pressures and temperatures. The energy at the collapse point is in some cases sufficient to dissociate the gas molecules in the bubble, which recombine radiatively to produce light, a process known as sonoluminescence (Crum 1994, Brenner *et al.* 2002). In the studies of Ahmad *et al.* (1988), Lumley *et al.* (1993) and Roy *et al.* (1994), sonoluminescence was used to detect transient cavitation.

Transient cavitation only occurs when the file can vibrate freely in the canal or when the file touches lightly (unintentionally) the canal wall (Lumley *et al.* 1993, Roy *et al.* 1994). Increased (intentional) contact with the canal wall, as in UI, excludes transient cavitation. The surface property of the file is important for the enhancement of cavitation (Roy *et al.* 1994). In their study a smooth file with sharp edges and a square cross-section produced significantly more transient cavitation than a normal K-file. The sharp edges could have induced so-called edge cavitation. The transient cavitation was visible at the apical end and along the length of the file. When the file came in contact with the canal wall, stable cavitation was affected less than transient cavitation and was mainly seen at the midpoint of the file (Roy *et al.* 1994). A pre-shaped file brought into a curved canal is more likely to produce transient cavitation rather than a straight file (Roy *et al.* 1994). Other researchers claim that cavitation provides only minor benefit in ultrasonic irrigation, or that it does not occur at all (Walmsley 1987, Ahmad *et al.* 1988, Lumley *et al.* 1988).

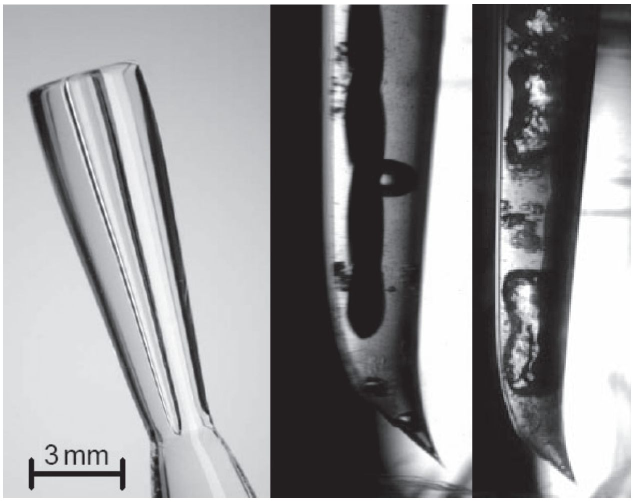

Figure 2 Left: Glass root canal model allowing optical access to the vibrating file for high-speed visualization of ultrasonic irrigation. Middle: File in operation captured at microseconds timescale displaying both transient and inertial cavitation phenomena and in addition local streaming patterns (only visible in video mode). Right: A high-speed recording of a noncutting K-file is shown, displaying vigorous microstreaming and collapsing cavitation bubbles.

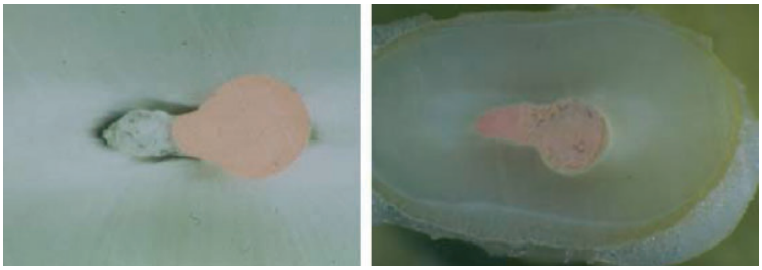

Figure 3 Dentine debris packed in oval shaped root canal after syringe irrigation (left) and clean oval canal after 3 min of PUI (right).

The effects and use of PUI

PUI versus syringe irrigation

After shaping the root canal, cleaning can be completed with PUI or a final flush of syringe irrigation. From the studies where PUI and syringe irrigation were compared, it can be concluded that PUI is more effective in removing remnants of pulp tissue and dentine debris (Goodman *et al.* 1985, Cameron 1987a, Metzler & Montgomery 1989, Cheung & Stock 1993, Lee *et al.* 2004b, Gutarts *et al.* 2005, Passarinho-Neto *et al.* 2006) and planktonic bacteria (Sjögren & Sundqvist 1987, Huque *et al.* 1998, Spoleti *et al.* 2003, Weber *et al.* 2003) (Fig. 3). In the studies by Goodman *et al.* (1985), Cheung & Stock (1993), Spoleti *et al.* (2003), Gutarts *et al.* (2005), Passarinho-Neto *et al.* (2006), the working volume of the experimental irrigant was standardized between the groups. In all these studies NaOCl was used as the irrigant except the study of Spoleti *et al.* (2003) and Weber *et al.* (2003), where sterile saline and chlorhexidine and NaOCl was used respectively.

In the study of Mayer *et al.* (2002) no significant difference was found between PUI and syringe irrigation in dentine debris removal from the root canal. Before activating ultrasonically the NaOCl, EDTA was left in the root canal. Removal of EDTA before the injection of 2 mL NaOCl in the root canal was not mentioned. EDTA inactivates the NaOCl and it is possible that this had an influence on the outcome.

PUI with NaOCl as irrigant

During PUI, NaOCl removes significantly more smear layer or bacteria from artificial smear layer, pulp tissue or dentine debris from the root canal than water (Cameron 1987b, Metzler & Montgomery 1989, Cheung & Stock 1993, Heard & Walton 1997, Türkün & Cengiz 1997, Huque *et al.* 1998, van der Sluis *et al.* 2006). The significant increase in dissolving capacity of organic material by NaOCl, when NaOCl is agitated by ultrasound (Moorer & Wesselink 1982) or when the temperature rises because of ultrasound (Cunningham & Balekjian 1980, Cameron 1988, Ahmad 1990) can be an explanation for the enhanced performance of NaOCl. When a greater concentration of NaOCl is used the efficacy appears to increase (Türkün & Cengiz 1997, Huque *et al.* 1998).

Removal of bacteria

The PUI results in a significant reduction of bacteria (Martin 1976, Collinson & Zakariasen 1986, Ahmad 1989), or shows significantly better results than syringe irrigation (Sjögren & Sundqvist 1987, Huque *et al.* 1998, Spoleti *et al.* 2003, Weber *et al.* 2003). Only in the study of Siqueira *et al.* (1997) the difference was not significant. In the study by Huque *et al.* (1998), PUI with 12% NaOCl as irrigant almost completely removed different types of planktonic bacteria from a parallel-sided canal by a streaming effect through the dentinal tubules.

Studies on the antibacterial effect of PUI have focused on the removal of planktonic bacteria through the flushing effect. The physical mechanisms describing the effect of ultrasonic irrigation on biofilms in the root canal are unknown, although cavitation has shown to be able to destroy or even remove a biofilm (Ohl *et al.* 2006).

Removal of the smear layer

Studies on smear layer removal by PUI are inconclusive. However, the various studies selected different types and concentrations of irrigant solution. When 3% NaOCl was used Cameron (1983) found complete removal of smear layer with 3 and 5 min of PUI; the results were confirmed in a subsequent study (Cameron 1987b). Alaçam (1987) could completely remove the smear layer after 3 min of PUI with 5% NaOCl and Huque *et al.* (1998) after 20 s PUI with 12% NaOCl. A 5% NaOCl solution during 3 min PUI could remove more smear layer than 0.5% NaOCl from the apical and middle part of the root canal (Türkün & Cengiz 1997).

Cheung & Stock (1993) could not completely remove the smear layer using 10 s PUI with 1% NaOCl, although PUI was significantly better than syringe irrigation. In the studies of Ciucchi *et al.* (1989) and Abbott *et al.* (1991) ultrasound did not enhance the removal of the smear layer when EDTA or a combination of EDTA and NaOCl was used as irrigant. On the other hand, PUI could significantly improve the smear layer removal of Savlon (0.03% chlorhexidine, 0.3% cetrimide). PUI with water as irrigant is unable to remove the smear layer (Cameron 1983, 1987b, Heard & Walton 1997, Türkün & Cengiz 1997, Huque *et al.* 1998). All studies show increased removal of the smear layer primarily from the coronal part of the root canal wall rather than the apical part, except for one study (Türkün & Cengiz 1997).

All these studies used the SEM technique to investigate the presence of smear layer. A disadvantage of this methodology is that only a very small part of the root canal can be evaluated and this is often not standardized.

PUI in curved canals

The PUI can also be effective in curved canals (Goodman *et al.* 1985, Metzler & Montgomery 1989, Jensen *et al.* 1999, Sabins *et al.* 2003, Gutarts *et al.* 2005) and the best result is obtained when the file is pre-bent (Ahmad *et al.* 1992, Lumley & Walmsley 1992). In the studies of Goodman *et al.* (1985), Metzler & Montgomery (1989), Jensen *et al.* (1999), Sabins *et al.* (2003), Gutarts *et al.* (2005), the apical portion of the root canal was examined, i.e. below the curve. When compared with syringe irrigation (Goodman *et al.* 1985, Metzler & Montgomery 1989, Gutarts *et al.* 2005) PUI performed significantly better.

PUI and the cleaning of the isthmus

Some studies specifically evaluated the cleaning efficacy of PUI in the isthmus which runs between two canals. Their results confirm a significantly cleaner isthmus when PUI is used compared with syringe irrigation (Goodman *et al.* 1985, Metzler & Montgomery 1989, Gutarts *et al.* 2005), which demonstrates that PUI has the potential to remove pulp tissue and dentine debris from remote areas of the root canal system untouched by endodontic instruments.

Ultrasonic versus sonic irrigation

Sonic irrigation is different from ultrasonic irrigation because it operates at a lower frequency. For sonic application the frequencies ranges from 1000 to 6000 Hz. Consequently, following equation 1, the streaming velocity of the irrigant will be lower. Moreover, the oscillating patterns of the sonic instruments are different. They have one node near the attachment of the file and one antinode at the tip of the file. When the movement of the sonic file is constrained, the sideway movement will disappear, but will result in a longitudinal vibration (Lumley *et al.* 1996).

Two studies report that PUI removed more dentine debris from the root canal than sonic irrigation (Stamos *et al.* 1987, Sabins *et al.* 2003), whilst in one study no significant difference was found (Jensen *et al.* 1999). In the study by Jensen *et al.* (1999), however, pre-shaping of the files was not mentioned and this may explain their findings. The positive relationship between streaming velocity and frequency can explain the higher efficiency of PUI versus sonic irrigation.

Heating of irrigant and root surface during PUI

Cameron (1988) reported a rise of the intracanal temperature from 37 to 45 °C close to the tip of the instrument and 37 °C away from the tip when the irrigant was ultrasonically activated for 30 s without replenishment. A cooling effect from 37 to 29 °C was recorded when the irrigant was replenished with a continuous flow of irrigant. The temperature of the irrigant was 25 °C. The external temperature stabilized at 32 °C during a continuous flow of the irrigant and reached a maximum of 40 °C in 30 s without continuous flow. Ahmad (1990) reported a mean rise of temperature of 0.6 °C during a continuous flow of irrigant. The initial temperature of the irrigant was 20 °C. A rise of temperature within these ranges will not cause pathological temperature rises in the periodontal ligament.

PUI parameters

Taper of the file and diameter of the root canal

The taper and diameter of the root canal have an influence on the efficacy of PUI in dentine debris removal from the root canal. In the studies by Lee *et al.* (2004a) and van der Sluis *et al.* (2005b), 3 min of PUI with 2% NaOCl was performed in each canal. From their results, it can be concluded that within certain limits (size 20, taper 0.04 to size 20, taper 0.10) the greater the taper the more dentine debris can be removed.

Application of irrigant during PUI

Two flushing methods can be used during PUI, namely a continuous flush of irrigant from the ultrasonic handpiece or an intermittent flush method using syringe delivery (Cameron 1988). In the intermittent flush method, the irrigant is injected into the root canal by a syringe, and replenished several times after each ultrasonic activation. During ultrasonic activation, an ultrasonically oscillating instrument (file or smooth wire) will activate the irrigant in the root canal such that microorganisms, dentine debris and organic tissue will be detached from the root canal wall and be absorbed or dissolved in the irrigant (Weller *et al.* 1980, Moorer & Wesselink 1982). Hereafter, the root canal is flushed with 2 mL of fresh irrigant to remove the remnants from the root canal. Both flushing methods were equally effective in removing dentine debris from the root canal in an *ex vivo* model when the irrigation time was set at 3 min (van der Sluis *et al.* 2006).

Druttman & Stock (1989) concluded that using a continuous flush of irrigant, the irrigant replacement in the root canal system is more likely to be influenced by time than by the volume used (Druttman & Stock 1989). This is confirmed by a study of Passarinho-Neto *et al.* (2006), where 5 min of PUI removed more dentine debris from the root canal than 1 min using a continuous flow of NaOCl, when the volume was the same in both groups. When the irrigant is injected in the root canal by a syringe, the amount of irrigant flowing through the apical region of the canal can be controlled because both volume and depth of syringe penetration are known, this is not possible using the continuous flush from the handpiece. The apical flow is important because frequent replenishment of NaOCl is essential.

Irrigation time

The influence of irrigation time on the efficacy of PUI is not clear. One study claimed an increased removal of the smear layer after 5 min of PUI as opposed to 3 min (Cameron 1983). In the study of Sabins *et al.* (2003), no significant difference was found between 30 and 60 s of PUI in dentine debris removal from the root canal. In their study, instead of a continuous flow of NaOCl during PUI, the NaOCl was injected in the root canal by a syringe and not refreshed during the ultrasonic activation of NaOCl.

PUI with a smooth wire

A smooth wire is as effective as a normal cutting file in dentine debris removal during PUI (van der Sluis *et al.* 2005a). It seems preferable to use a smooth wire during PUI because it does not intentionally cut into the root canal wall and it may, therefore, prevent aberrant root canal shapes or perforation of the (apical) root (Mayer *et al.* 2002). Several studies (Weller *et al.* 1980, Cameron 1983, Goodman *et al.* 1985, Cameron 1987a,b, Türkün & Cengiz 1997, Mayer *et al.* 2002, Gutarts *et al.* 2005) have used smooth wires, and demonstrated their effectiveness during PUI. The smooth wire used in the study by Gutarts *et al.* (2005) was in fact a hollow ultrasonically activated needle through which the irrigant was delivered into the root canal.

Discussion

Acoustic microstreaming or cavitation play an important role in the efficacy of PUI. However, the details concerning those mechanism have not been clarified. An accurate description of the streaming pattern of the irrigant 'in the root canal' during PUI for instance is still not available. Therefore, the exact physical mechanisms responsible for the efficacy of PUI remain uncertain.

In some of the studies large standard deviations have been reported, indicating a substantial variation in the efficacy of PUI. An explanation could be that it is difficult to standardize the positioning of the ultrasonically activated instrument in the centre of the root canal and to standardize the displacement amplitude as a small constraint in the canal will change the amplitude. This will have a direct effect on the efficacy of PUI. This problem can most probably be overcome by increasing the frequency of the ultrasound. Then the streaming velocity of the irrigant will be so strong that a small change in the position of the instrument will make little difference.

Water as the irrigant appears to be less efficient than NaOCl during PUI. The differences in the physical properties of NaOCl and water could have an effect on the transmission of ultrasound energy by to the irrigant. For example, bubbles formed in salt water tend to be more numerous, particularly the smallest bubbles, and are less prone to coalesce than bubbles in fresh water (Leighton 1994). Vapour (chloride when NaOCl is used) could diffuse into the bubble during bubble expansion and the bubble dynamics depend on the concentration of the gas dissolved in the liquid, the temperature of the liquid and amounts of surface-active impurities (Brenner *et al.* 2002). These factors may explain why PUI with sterile saline (0.9% NaCl) removed significantly more planktonic bacteria from the root canal than syringe irrigation of saline although saline does not dissolve organic tissue and is not bactericidal (Spoleti *et al.* 2003). Water did not show a significant difference in the removal of dentine debris or planktonic bacteria when syringe irrigation and PUI were compared (Walker & del Rio 1989, Cheung & Stock 1993, Huque *et al.* 1998).

Subject to debate is the efficacy of PUI in curved canals. In the papers discussed in this review, the curvature of the roots was moderate <35 (Schneider 1971) and therefore pre-shaping of the file was possible, which may in part explain the positive results. Another explanation could be that PUI is performed after the root canal has been shaped. Therefore, the apical root canal is widened and there is simply more space for the file to move freely in the irrigant, even when the ultrasonically activated instrument does not reach the full working length (Krell *et al.* 1988). Furthermore, Roy *et al.* (1994) showed that transient cavitation could occur in curved canals (but only when the file was pre-shaped) creating a highly active streaming pattern in curved canals.

Conclusion

Based on this literature review it is concluded that PUI appears to be an adjunctive treatment for cleaning the root canal system and that PUI is more effective than syringe irrigation. More research is needed to clarify the underlying physical mechanisms through which PUI exerts its efficacy.

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